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Prospective analysis of the flows of certain rare earths in Europe at the 2020 horizon

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ABSTRACT

This paper proposes a forecast of certain rare earth flows in Europe at the 2020 horizon, based on an analysis of trends influencing various actors of the rare earth industry along the value chain. While 2020 is indicated as the forecast horizon, the analysis should be considered as more representative of the next decade. The rare earths considered here are used in applications that are important for a low-carbon energy transition and/or have a significant recycling potential: NdFeB magnets (Pr, Nd, Dy), NiMH batteries (Pr, Nd) and fluorescent lamp phosphors (Eu, Tb, Y). An analysis of major trends affecting the rare earth industry in Europe along the value chain (including extraction, separation, fabrication, manufacture, use and recycling), helps to build a scenario for a material flow analysis of these rare earths in Europe. The scenario assumes in particular that during the next decade, there exists a rare earth mine in production in Europe (with Norra Kärr in Sweden as a most likely candidate) and also that recycling is in line with targets proposed in recent European legislation. Results are presented in the form of Sankey diagrams which help visualize the various flows for the three applications. For example, calculations forecast flows from extraction to separation of Pr, Nd and Dy for magnet applications in Europe, on the order of 310 tons, 980 tons and 80 tons rare earth metal resp., while recycled flows are 35 tons, 110 tons and 30 tons resp. Calculations illustrate how the relative contribution of recycling to supply strongly depends on the situation with respect to demand. Considering the balance between supply and demand, it is not anticipated any significant shortage of rare earth supply in Europe at the 2020 horizon, barring any new geopolitical crisis involving China. For some heavy rare earths, supply will in fact largely outweigh demand, as for example Europium due to the phasing out of fluorescent lights by LEDs.

1. Introduction

Rare earth elements (REE) are a group of 14 lanthanides (excluding promethium; Pm, which has no stable or even long-life isotope), to which yttrium (Y) is added (and sometimes scandium; Sc). As in Wall (2014), we distinguish light REE (LREE; La, Ce, Pr, Nd, Sm) and heavy REE (HREE; Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, including Y). Rare earths occur in nature as rare earth oxides (REO; e.g., Eu_2O_3, Tb_4O_7, Y_2O_3) within minerals (e.g., bastnaesite and monazite) and are transformed into metals and compounds using metallurgical processes. The mass conversion from REO to REE metal is a stoichiometric conversion based on the REO atomic formula (on average, conversion from REO to REE metal is obtained by multiplying by 0.85). Rare earths have received considerable attention in the past 5 years, partly as a result of the dramatic rare earth price surge that occurred in 2011 following the tightening of Chinese rare earth export quotas which sparked a wave of speculation on prices. Since 2011 speculation has subsided, although prices are still above pre-2011 values. For example, while the prices of dysprosium (Dy) and terbium (Tb) over the period from 2002 to 2003 were on average 32 $US/kg and 204 $US/kg respectively (price FOB China; "free on board"), they reached a peak of 3410 $US and 5110 $US in July 2011, and have now (July 2015) subsided to around 323 $US and 705 $US (and decreasing). The crisis has nevertheless acted as a catalyst at a global scale to prompt policy makers to examine more closely the issue of REE supply and potential risks for industry.

The analysis of risks of supply shortage and potential damages for industrial sectors is called criticality analysis. Notable examples include EC (2014), Graedel et al. (2012), DOE (2011), NRC (2008). In 2014 the European Commission published a revised list of minerals

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deemed critical for the European Union (EU; EC, 2014). While in the previous list, rare earths were identified as a single group of raw materials, the revised list distinguishes between LREE and HREE, since HREE are more "rare" in nature than LREE. In the earth's crust, concentrations of LREE (e.g., Ce, La, Nd, Pr) are similar to those of base metals (Zn, Cu, Pb), while concentrations of HREE (e.g., Eu, Tb) are analogous to those of rare and precious metals (e.g., Ta, Ag, Au; Rudnick and Gao, 2003). Scarcity of primary sources of REE is related to the relative paucity of natural phenomena leading to localised high REE concentrations (deposits) compared to the base metals mentioned above, but also to China's quasi-monopoly in terms of rare earth ore extraction. China controls close to 90% of global REO production although it holds only approximately one third of identified world resources. In order to reduce China's monopoly, several rare earth mines outside China started or resumed production (Mountain Pass in the US and Mount Weld in Australia). These mines are rich in LREE but not in HREE, which today are extracted nearly exclusively from mines located in the south of China.

Rare earths are considered critical because they are essential to several strategic industrial sectors. The most prominent technology, that is pulling global demand for rare earths, is permanent magnets. Neodymium–Iron–Boron (NdFeB) magnets are the strongest permanent magnets commercially available today. They are used in a wide variety of applications and are a key component of the transition towards a low-carbon energy economy (Moss et al., 2013). The uncertainty with respect to the future supply of rare earths for satisfying the demand of key technologies such as direct drive wind turbines, electric and hybrid vehicles, low-energy lighting, has prompted a number of prospective studies on future rare earth supply and demand. For example Habib and Wenzel (2014) underline the importance of primary sources of REE for meeting demand for clean energy technologies. Hoenderdaal et al. (2013) examine the threat posed by Dy shortage for the development of green energy technologies and suggest that in the short term (2020), Dy demand will outstrip supply. Alonso et al. (2012) performed a scenario analysis to provide estimates of Nd and Dy demand for technologies aimed at stabilizing atmospheric CO_2 emissions. The authors suggest that without efficient recycling and technologies that use lower amounts of these REE, demand for Nd and Dy could increase by factors of 7 and 26, respectively, over the next 25 years. Elshkaki and Graedel (2014) also focus on Dy supply and highlight in particular the so-called balance problem (see also Binnemans et al., 2013). As mentioned above, most rare earth deposits in the world are rich in LREE but not in HREE and so in order to obtain one ton of Dy oxide, it is necessary to produce quantities of other rare earths (e.g., La, Ce, Y) that are at least ten times higher. Note that the relative distribution of REE in a typical LREE ore is: 45–50% Ce, 20–25% La, 12–20% Nd and 4–5% Pr. Elshkaki and Graedel (2014) therefore underline the importance of producing HREE such as Dy from HREE-rich mines, in order to limit the oversupply of other REE. Rademaker et al. (2013) performed an analysis of future demand at a global, but also at a European scale. The authors examine to what extent the recycling of end-of-life products can contribute to demand for REE and highlight the influence of application lifetimes (in-use) which offset flows of end-of-life products with respect to supply.

In this paper we propose an analysis of future demand for certain rare earths in Europe at the horizon 2020. While this horizon is presented as a precise deadline, the analysis should better be considered as representative of the next decade, as the selected hypotheses are inevitably affected by significant uncertainty. Rare earths considered here are those used in applications that are important for a low-carbon energy transition and/or have a significant recycling potential: NdFeB magnets (Pr, Nd, Dy), nickel-metal-hydride (NiMH) batteries (Pr, Nd) and fluorescent lamp phosphors (Eu, Tb, Y). While La and Ce are also recovered during, e.g., battery and fluorescent lamp recycling, these elements are not considered as critical and were therefore not detailed in this study. While some authors propose prospective analyses at a horizon of 2050 or more, it was preferred here to consider a closer deadline in order to reduce the uncertainty of the analysis. Any prospective analysis of rare earths in Europe is affected by considerable uncertainty regarding in particular: (i) the wide range of applications, each with its own market dynamics, (ii) the possible evolution of the Chinese position, with a situation of quasi-monopoly with respect to supply and (iii) the difficulty to limit the analysis to Europe while markets and value chains are in essence global. However, hypotheses regarding future evolutions were made based on published information and on internal Solvay information for the case of lamp phosphors. A starting point for the analysis presented herein is the material flow analysis (MFA) presented in Guyonnet et al. (2015) for rare earth flows and stocks in Europe in 2010, as the latter MFA and the prospective analysis presented herein were part of the same project. There have been very few MFA analyses performed for rare earths at the scale of the EU (Rademaker et al., 2013), as most analyses are at a global scale (e.g., Du and Graedel, 2011a,b,c) or for countries outside the EU (e.g., Swain et al., 2015). An important aspect of the work presented here is that it considers expected evolutions of the rare earth industry along the value chain, taking into account specialized market information available at Solvay; one of the main European actors of the rare earth industry. Previously-published prospective analyses often tend to neglect trends affecting the actual actors of the value chain.

2. Methods

2.1. Material flow analysis

Material flow analysis is used here to quantify flows of REE in Europe at the 2020 horizon based on a plausible scenario. The results of the analysis are presented in the form of Sankey diagrams (Brunner and Rechberger, 2004) which are a particularly didactic way of communicating the results of MFA. A particular feature of such diagrams is that flows are depicted by arrows, the widths of which are shown proportionally to the flow quantities. This feature makes it very easy, especially for a non-technical audience, to see where the major flows in the value chain are. A first step in MFA is system definition. Fig. 1 shows the value chain of the system investigated for the MFA of Nd in NdFeB permanent magnets. The figure shows a number of processes summarizing the REE value chain, some of which are connected by arrows symbolizing flows. These processes may or may not include stocks. The boundary of the system is the European Union. While all 28 countries of the EU were included in the analysis, only certain countries have a significant share of imports and/or exports of rare earth elements (i.e., Austria, Estonia, France, Germany and the United Kingdom).

Starting the description at the upstream end of the value chain, it is seen that the process "Lithosphere" (which represents the extraction of primary sources of Nd) straddles the boundary of the system: for geological and economic reasons, it was chosen to consider the lithosphere at the scale of continental Europe (including the Scandinavian shield, with the Kola Peninsula in Russia and Turkey) plus Greenland. As a first step in the magnet manufacturing process, there is the fabrication of NdFeB alloy for magnet applications. In Europe, the actual manufacture of NdFeB magnets is performed by only one company; Vacuumschmelze in Germany and its subsidiary NeoRem in Finland. Magnets are incorporated in applications in the "Applications" process, while these

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